PROGRESSIVE FAILURE ANALYSIS OF THIN WALLED COMPOSITE TUBES UNDER LOW ENERGY IMPACT

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ABSTRACT

Composite failure criteria have been developed for dynamic analysis of composite structures. The proposed progressive failure criteria have been integrated into an explicit dynamic analysis code for failure prediction of thin composite tubes subjected to drop weight impact tests. The results provide good correlation with experimental data for impact force histories and some critical damage modes.

INTRODUCTION

High stiffness and high strength fiber composites such as graphite/epoxy and Kevlar/epoxy are now being widely used in the construction of pressure vessels. Filament wound composite tubes have been utilized to meet the demanding light weight requirements. However, such composite systems are susceptible to impact damage during assembly and handling. Low energy impact caused by dropping tools, for instance, typically results in surface and part-through damage. The burst strength of the pressurized tubes can be significantly reduced by the presence of this damage.

In order to develop light-weight composite tubes with enhanced reliability, it is necessary to identify and fully utilize the mechanisms that can effectively mitigate the impact damage. An effective analytical composite design methodology should be able to account for and accommodate composite failure modes and the corresponding property changes. The current approach is to determine composite structural damage based on the stress distribution obtained from elastic solutions, e.g., [1,2]. However, damage prediction based on this approach may not be reliable, since the effect of damage progression is neglected. This may lead to misinterpretation of failure mechanisms and the influence of various structural and material parameters. On the other hand, there are dynamic analysis codes which are able to model the progressive failure of structures made with homogeneous materials. The ability to accurately predict the deformation and failure progression of composite materials under low energy impact is imperative for effective design of composite tubes.

Low energy impact damage in composite structures has been the subject of numerous studies, e.g., [3-11]. However, few studies have been reported on modeling the progressive failure in thin shell composites. In order to model the nature of the progressive failure expected from laminates under low energy conditions, it is necessary to integrate the failure models into the load step/time step regime of a dynamic analysis code. The integration of appropriate failure models provides the opportunity to accurately describe the nonlinear behavior of composite materials due to the progression of local composite damage within the macroscopic continuum computer code. The capability of utilizing the proposed approach to model the composite structural response under low energy impact conditions has been critically evaluated in this work. Analyses have been performed to predict the load-time history and damage in composite tubes subjected to drop weight impact testing.

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COMPOSITE PROGRESSIVE FAILURE MODEL

In general, damage modes, which may occur in a composite structure subjected to transverse impact loading, are matrix tensile cracking, matrix compressive/shear failure, ply separation (delamination) and fiber breakage (tensile or compressive). Under these conditions, all six stress components are generally necessary to characterize and discriminate among the various possible failure modes. Failure criteria based on the 3D stresses in a unidirectional composite layer, with improved progressive failure modeling capability have been developed in this study. The layer failure criteria define the initiation of fiber and matrix damage modes by adopting the well-known Hashin failure functions [12]. Initiation of the delamination mode is then determined by scaling the matrix damage functions to a higher level of stresses. Such generalization ensures that delamination occurs subsequent to the layer matrix failure. Failure initiation criteria are applied directly to characterize the progression of the associated failure modes.

The layer failure criteria and the associated property degradation models are described as follows. Note that all failure criteria are expressed in terms of stress components based on ply level stresses $(\sigma_1, \sigma_2, \sigma_3, \tau_{12}, \tau_{23}, \tau_{31})$ with 1,2 and 3 denoting the fiber, in-plane transverse and out-of-plane directions, respectively.

Fiber Failure Modes

The fiber tensile mode is assumed to depend only on the axial stress, and the fiber tensile failure is predicted when

$$[\frac{\sigma_1}{S_1^t}]^2 = 1 \tag{1}$$

where S_1^t is the axial tensile strength. This criterion is applicable when σ_1 is positive, and is used to predict a failure mode characterized by fiber breakage.

When fiber failure in tension is predicted in a layer, the load carrying capacity of that layer is completely eliminated. The axial modulus E_a, the transverse modulus E_t, the axial shear modulus G_a, and the transverse shear modulus G_t are all reduced to zero. When σ_1 is compressive it is assumed that failure is characterized by fiber buckling and is only dependent upon σ_1. The compressive fiber mode failure criterion is governed by the maximum stress criterion

$$[\frac{\sigma_1}{S_1^c}]^2 = 1 \tag{2}$$

where S_1^c is the axial compressive strength of the ply.

For compressive fiber failure, the layer is assumed to carry a residual axial load, while the transverse load carrying capacity is reduced to zero, $E_t = G_a = G_t = 0$. When the compressive axial stress in a layer reaches the compressive axial strength S_1^C, the axial layer stress is assumed to be reduced to the residual strength S_1^{RC}. The axial stress is assumed to remain constant, i.e., $\sigma_1 = -S_1^{RC}$, for continuous compressive loading, while the subsequent unloading curve follows a reduced axial modulus as shown in Figure 1. For a layer with axial compressive failure, the layer residual tensile strength is assumed to be S_1^{RC} beyond which the layer is failed completely. In this study, S_1^{RC} was assumed to have the value of $0.1S_1^C$.

Matrix Failure Modes

Matrix mode failure is characterized by cracks running parallel to the fibers. Failure is described as being tensile or compressive, depending upon the sign of the quantity $(\sigma_2 + \sigma_3)$, as suggested in [12]. Both matrix mode failure criteria assume quadratic interactions between the transverse stresses (both in-plane, σ_2, and through the thickness, σ_3), the maximum shear in the transverse plane, and the maximum axial shear.

When $(\sigma_2 + \sigma_3)$ is positive, the tensile mode criterion is used. This criterion is given by

$$F_t^2 = [\frac{\sigma_2 + \sigma_3}{S_2^t}]^2 + \frac{(\tau_{23}^2 - \sigma_2 \sigma_3)}{S_{23}^2} + \frac{(\tau_{12}^2 + \tau_{31}^2)}{S_{12}^2} = 1 \tag{3}$$

where S_2^t, S_{23} and S_{12} are the transverse tensile, transverse shear and axial shear strengths, respectively.

For $(\sigma_2 + \sigma_3)$ negative, the compressive failure criterion is given by

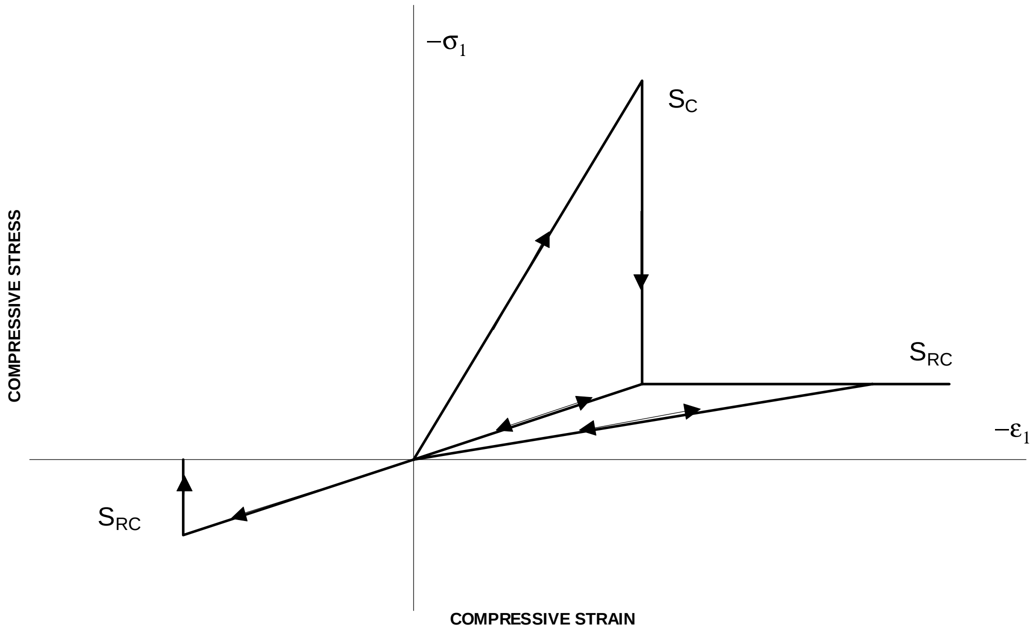


Figure 1. A Compressive Fiber Failure Model

$$F_c^2 = \frac{\left[\frac{\sigma_2 - \sigma_3}{2}\right]^2 + \tau_{23}^2}{S_{23}^2} + \frac{(\tau_{12}^2 + \tau_{31}^2)}{S_{12}^2} = 1 \qquad (4)$$

which is a simple quadratic interaction between the maximum transverse and axial shear stresses. Failure predicted by this criterion is referred to as compressive/shear failure.

No stiffness reduction is assumed after matrix failure occurred. This is because transverse matrix cracks alone usually do not have significant effect on the laminate stiffness.

Delamination Modes

A delamination is a crack which runs in the resin-rich area between plies with different fiber orientation. Delamination caused by transverse impact usually occurs after an energy threshold has been reached. It has been observed that delamination only occurs in the presence of matrix cracks. Taking this into consideration, the initiation of the delamination mode is determined by scaling the matrix damage functions to higher level of stresses.

For $(\sigma_2 + \sigma_3)$ positive, the tensile/shear delamination mode is given by

$$S^2 F_t^2 = 1 \qquad (5)$$

For $(\sigma_2 + \sigma_3)$ negative, the compressive/shear delamination mode is given by

$$S^2 F_c^2 = 1 \qquad (6)$$

where F_t and F_c are the damage functions given by equations (3) and (4), respectively, and S is used as a scale factor which can be determined from fitting the analytical prediction to experimental data for the delamination area.

When delamination is predicted, the transverse modulus, the axial and transverse shear moduli are reduced to zero in the layer with matrix damage, i.e., $E_t = G_a = G_t = 0$. However, the layer axial modulus is unchanged.

The progressive failure criteria have been established to effectively characterize the composite layer properties under the influence of progressive damage while maintaining computational simplicity within the dynamic analysis codes. During progressive failure analysis, the failure criteria are used to identify and discriminate the various failure modes active, and thereby make the necessary adjustments to the effective layer stiffnesses.

The failure model has been encoded as a user-defined subroutine for the use in LS-DYNA [13]. The failure model is applicable to thin shell elements and 3D brick elements. It allows definition of the failure criteria for each layer in an arbitrary composite lay-up configuration within a shell element.

IMPACT DAMAGE ANALYSIS AND DATA CORRELATION

The integrated dynamic code was used to predict the load-time histories for a composite tube subjected to the drop weight impact test. The finite element models for the tube and an impactor were generated (Figure 2). Only one quadrant of the impact system was modeled due to the geometric symmetry and the use of effective material properties of the composite tube. The tube, which had a 5-inch diameter and a 12.5-inch length, was modeled using 4-noded shell elements and a laminated composite material model. The impactor, which was a one-half inch solid steel cylinder with a hemispherical tip, was modeled using 8-noded brick elements. Note that the extra weight was lumped at the end of the impactor to provide a total impact weight of 11.34 lbs. The impactor was given an initial velocity for performing dynamic analysis.

Symmetry conditions at the xz boundary plane were imposed by restricting the y displacement and x and z rotations, while at the symmetric yz plane, x displacement and y and z rotations were restricted. A stationary 45^o-inclined rigid wall was imposed on the bottom part of the tube to simulate the V-block test fixture on which the test tube was initially placed. Surface-to-surface contact commands were specified to simulate the contact conditions between the tube and impactor and also between the tube and the restraining rigid wall.

The composite cylinder consisted of a [30/-30/90/90/30/-30/90/90] lay-up configuration for which the reference direction coincides with the axis of the tube and the last 90^0 ply is the outermost layer. Note from Figure 2 that 32 through the thickness integration points were used for the elements in the area adjacent to the initial impact point. The integration point numbers were then reduced to 16 and 8 in the areas away from the impact point. The thickness of the tube was 0.055 inch. Material properties used for a transversely isotropic unidirectional IM6/Epoxy layer are E_a=165.5GPa (24Msi), E_t=10.3GPa (1.5Msi), ν_a=0.32, ν_t=0.36, G_a=5.5GPa (0.8Msi), S_1^t=2.55GPa (370ksi), S_1^c=1.58GPa (229ksi), S_2^t=0.04GPa (5.8ksi), S_2^c=0.14GPa (20.3ksi), S_{12}=0.12GPa (17.4ksi), S_{23}=0.07GPa (10.2ksi). The isotropic elastic properties of the steel impactor are: E=207GPa (30Msi), ν=0.35. The densities for the composite material and the steel are 1.6g/cc (1.49x10^{-4}lbs-sec^2/in^4) and 82.9g/cc (77.33x10^{-4}lbs-sec^2/in^4), respectively.

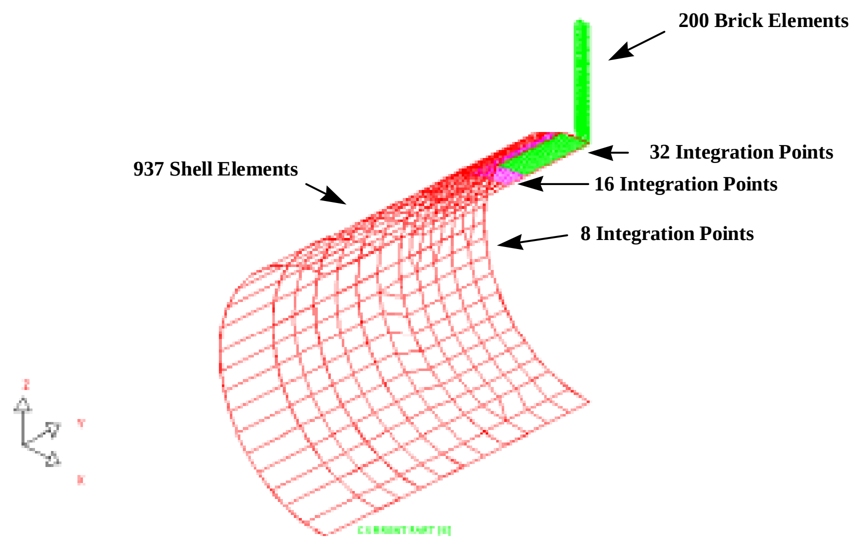


Figure 2. Finite Element Model of MICOM Tube

Accurate prediction of the impact contact force is essential for characterizing the deformation and failure in the composite tube. In this work, the contact analysis capability provided within LS-DYNA was chosen to perform the contact analysis between the impactor and the target composite shell. A surface-to-surface contact option procedure was utilized to perform the contact analysis. In this approach, nodes lying on a slave surface are constrained to slide on a master surface (the side with higher stiffness) after impact and must remain on the master surface until a tensile force develops between the node and the surface [14]. In the case of shell elements, shell thicknesses are automatically accounted for in the analysis.

The computed contact force histories are compared to the experimental contact force data in Figures 3 and 4 for impact velocities of 3.92 ft/sec and 5.08 ft/sec, respectively. For both velocities, good agreement is seen between the experimental and analytical results within the first 3 msec of impact before the damage initiated. Within this time range, the analyses provide approximately the same frequencies and peak-to-peak magnitudes of the experimental data in both cases. This correlation lends credibility to the model as a whole, and justifies the use of the chosen contact model.

Beyond the damage initiation time, the prediction of the impact force history is strongly affected by the use of failure criteria. It is seen from Figures 3 and 4 that the results with the consideration of progressive fiber damage provide good overall agreement with the experiments. The progressive fiber failure yields peak loads which are less than 6% above the maximum measured values. The analysis neglecting damage yields peak loads which are at least 15% above the test values.

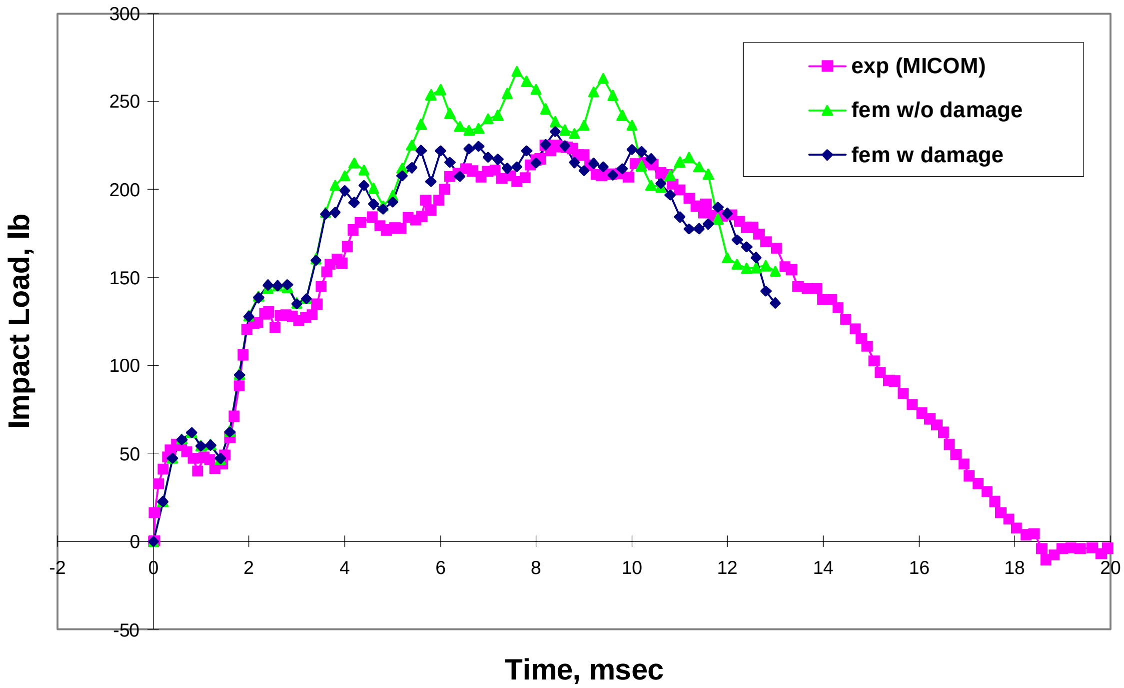


Figure 3. Comparison of Predicted and Measured Impact Force Histories for a [30/-30/90//90/30/-30/90/90] Tube under 3.92ft/sec Impact Velocity

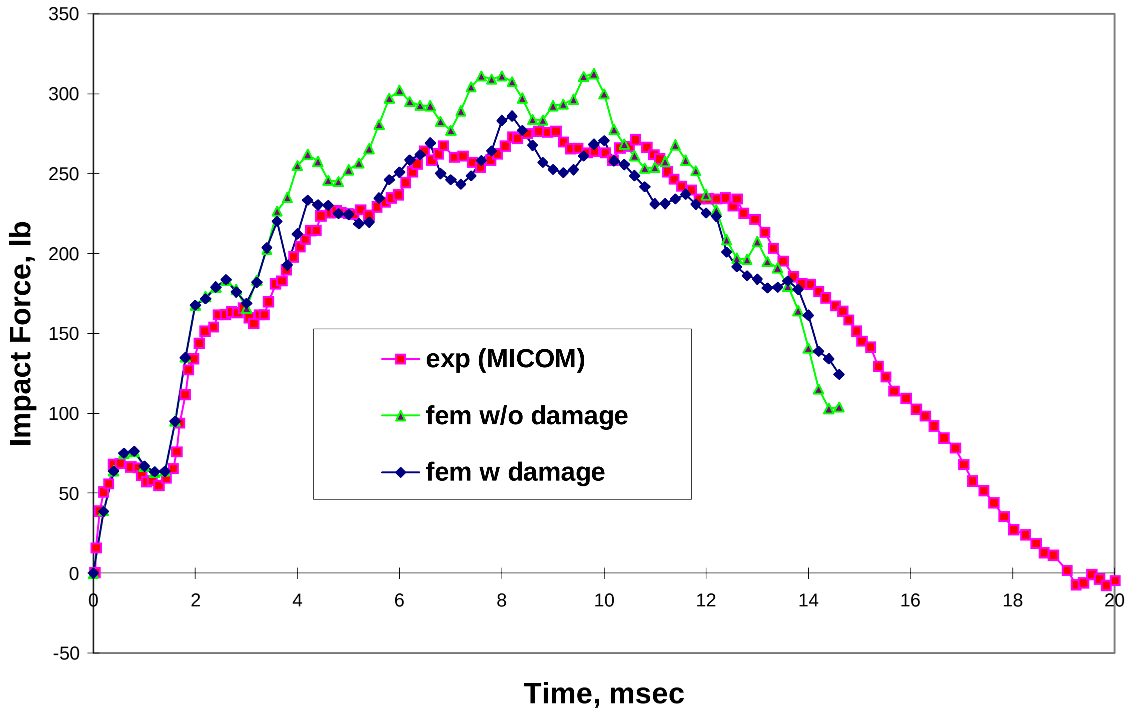


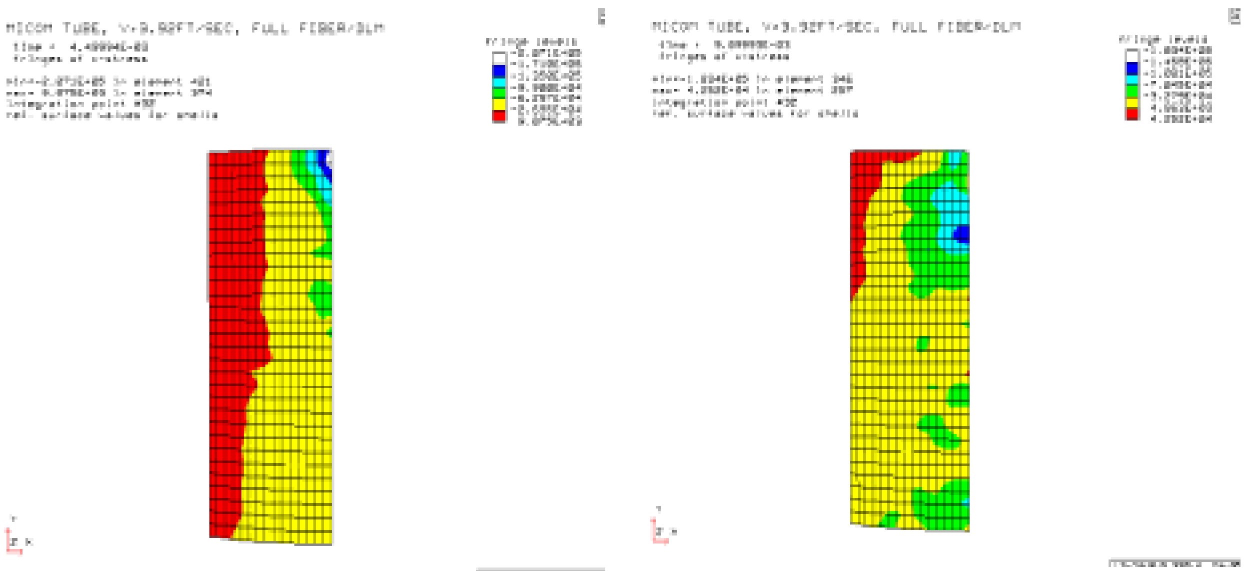
Figure 4. Comparison of Predicted and Measured Impact Force Histories for a [30/-30/90//90/30/-30/90/90] Tube under 5.1ft/sec Impact Velocity

Typical stress distributions in composite layers for an impact velocity of 3.98 ft/sec are shown in Figure 5 for the case with progressive fiber damage. Figure 5a shows the contours of hoop stress in the outermost 90^0 layer in the area adjacent to the impact point at about 3.9 msec from the contact initiation. It is seen that the stress concentration at the contact area prior to fiber compressive failure approached the fiber compressive strength of 230 ksi. When loaded beyond this point, fiber compressive failure initiated in the outermost hoop layers in the contact element and propagated into the adjacent elements along the tube axial direction. At 9.0 msec, the post failure contours of Figure 5b show the unloaded stress distribution in these elements with damaged hoop fibers.

The effect of fiber damage on the impact load history can be readily seen from Figure 3 by comparing the predicted results with and without fiber damage. The initiation of the compressive fiber failure occurred in the outermost 90^0 layer at 3.9 msec and caused immediate load reduction. It is also seen in Figure 3 that the failure progression in the outermost 90^0 layers provided further reduction of the impact force. The reduction in impact loading is mainly due to the reduction of local shell stiffness which is dominated by the failure of the outermost 90^0 layers.

The progressive failure analysis provides reasonable correlation with measured data for some damage modes which may be critical to the residual strengths of the thin composite tube. These include (1) the fiber crack length of the surface hoop layer, Figure 6 and (2) the fiber crack depth in the hoop layers, Figure 7.

Prior Fiber Comp. Failure **Post Failure**



(a) (b)

Figure 5. Results - Hoop Stress Contours in Outmost 90 Layer (intg. pt. 32) for V=3.92 ft/sec with Full Fiber Damage

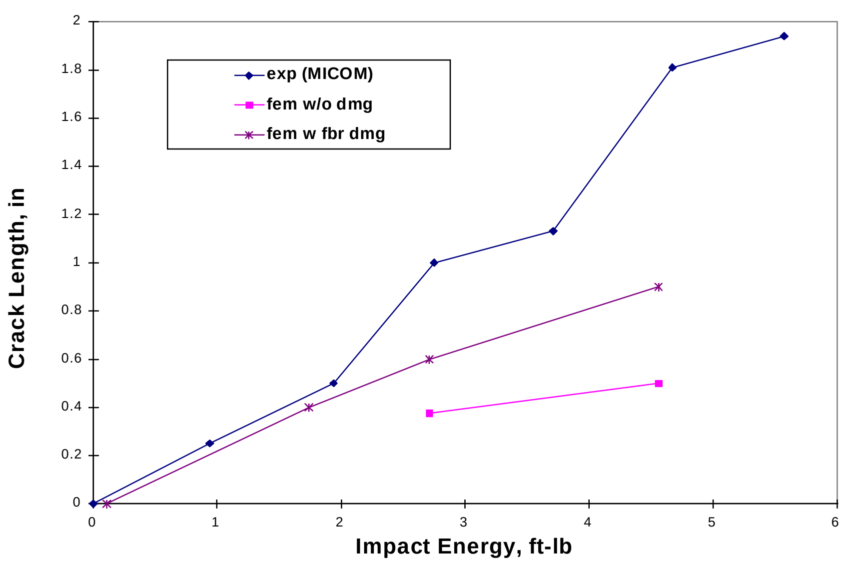


Figure 6. Comparison of Measured and Predicted Fiber Crack Length due to Impact Energy

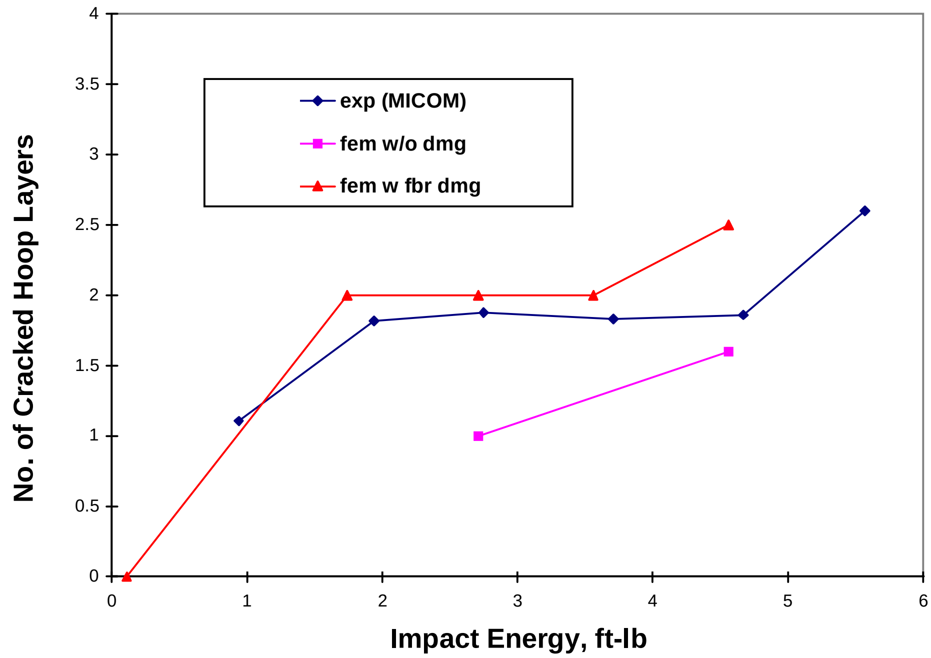


Figure 7. Comparison of Measured and Predicted Hoop-Ply Crack Depth Due to Impact Energy. Experimental Values are Estimated from Residual Burst Pressures by Neglecting all the Off-Axis Layers

CONCLUSIONS

A composite failure model has been successfully incorporated into the commercial code LS-DYNA for predicting progressive failure of thin composite structures under low energy impact conditions. This integration analysis code provides the opportunity to effectively describe the nonlinear behavior of composite materials due to the progression of local composite damage, within the macroscopic continuum computer code. The availability of such a dynamic failure analysis code will greatly facilitate the development of light-weight composite pressure vessels with enhanced impact resistance capability.

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